Status of a UAVSAR Designed for Repeat Pass Interferometry for Deformation Measurements

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Abstract — **NASA's Jet Propulsion Laboratory is currently implementing a reconfigurable polarimetric L-band synthetic aperture radar (SAR), specifically designed to acquire airborne repeat track interferometric (RTI) SAR data, also known as differential interferometric measurements. Differential interferometry can provide key deformation measurements, important for the scientific studies of Earthquakes and volcanoes. Using precision real-time GPS and a sensor controlled flight management system, the system will be able to fly predefined paths with great precision. The expected performance of the flight control system will constrain the flight path to be within a 10 m diameter tube about the desired flight track. The radar will be designed to operate on a UAV (Unpiloted Arial Vehicle) but will initially be demonstrated on a minimally piloted vehicle (MPV), such as the Proteus built by Scaled Composites or on a NASA Gulfstream III. The radar design is a fully polarimetric with an 80 MHz bandwidth (2 m range resolution) and 16 km range swath. The antenna is an electronically steered along track to assure that the actual antenna pointing can be controlled independent of the wind direction and speed. Other features supported by the antenna include an elevation monopulse option and a pulse-to-pulse resteering capability that will enable some novel modes of operation. The system will nominally operate at 45,000 ft (13800 m). The program began out as an Instrument Incubator Project (IIP) funded by NASA Earth Science and Technology Office (ESTO).**

Index Terms — **electronically scanned array, interferometry, radar, SAR, UAV.**

I. Introduction

The solid earth science community is seeking earth deformation measurements at a variety of temporal scales, from seconds to decades. The NASA Solid Earth Science Working Group has recommended an observational program that includes both airborne and spaceborne capabilities and this is reflected in the NASA Earth Science Enterprise strategic plan [1]. Ultimately, scientists would like to have Earth deformation measurements on an hourly basis with global access, objectives best supported by a spaceborne high-orbit (e.g. geosynchronous) constellation of repeat-pass interferometric SAR satellites. The recommended first step in this observational program is a low-earth-orbit deformation satellite with a repeat period of roughly one week. The sub-orbital radar program enters the Earth Science Enterprise plan as a key supplemental capability, providing repeat-pass measurements at time scales much smaller than one week, potentially as short as twenty minutes.

Understanding the time varying nature of rapidly deforming features such as some volcanoes and glaciers or deformation from post seismic transients requires observational sampling intervals of a day or less to capture and model such events. In addition to providing unprecedented temporal detail of deformation of dynamic processes, the suborbital radar will be a testbed for understanding the observational needs for how rapid repeat observations would be acquired. This is a capability that the currently operational NASA AIRSAR system has demonstrated but cannot practically support for science experiments in its current configuration due to lack of track repeatability and beam pointing limitations.

Although satellites have been used for interferometric repeat track SAR mapping for close to 20 years, repeat track interferometry is much more difficult to implement from an airborne platform. Several organizations have acquired experimental airborne RTI data, however, without developing a capability to acquire significant amounts of high quality RTI data. The primary reason for this state of affairs is that 1) It is difficult to fly the same or nearly the same pass twice in the air, due to wind gusts, turbulence, etc. and 2) it is difficult to maintain the same antenna pointing on repeated passes due to varying cross-winds that lead to varying yaw angles.

The project started out as a proposal submitted to the NASA 2002 Instrument Incubator Program (IIP) to develop a repeat track measurement capability as an augmentation to the existing AIRSAR system. NASA accepted the proposal but directed that the proposed capability be fielded on a UAV or MPV platform to support the long-term interests of the airborne science community. After a year of study and experiments, NASA directed JPL to proceed with a full scale implementation. This paper outlines the status of the project, including a high level radar design.

II. System Requirements Overview

Repeat track interferometry not only requires that the phase centers of the radar antenna locations for the individual tracks are approximately coincident, it is also essential that the antenna look directions are identical to within a fraction of the beamwidth. Given that the wind can be substantially different at different times, even if the platform is capable of accurately repeating the desired track, the yaw angle of the aircraft can vary widely on different tracks due to different wind condition aloft. This we intend to mitigate by electronically steering a flush mounted antenna to the desired direction. As such, the UAVSAR system is a tight blending of platform and sensor capabilities.

Given that the temporal separation of the acquired track will have a wide range (minutes to years), it is required that the radar wavelength be long, however, at the same time the largest possible bandwidth is desired to increase the so-called critical baseline (maximal separation between antenna phase centers supporting interferometric observations). L-band is found to be a very attractive compromise with a quarter meter wavelength and 80 MHz of available bandwidth. Given an assumed operating altitude of 45,000 ft (13800 m), a near angle of incidence of approximately 25°, and an 80 MHz signal bandwidth – equivalent to a 2 meter slant range resolution, the perpendicular critical baseline is

$$B_{c\perp} = \frac{\rho \lambda \tan\theta}{2\Delta\rho} \approx \frac{15,800m\ 0.24m\ 0.6}{2 \cdot 2m} \approx 600m \qquad (1)$$

Although repeat track interferometry will generally work well over flat terrain, even at track separations up to on the order of a 1/10th of the critical baseline, practical effects such as terrain relief, knowledge of local elevations, slopes, and volume scattering will mean that robust RTI performance requires baselines significantly shorter. Based on our analysis, a 10 meter baseline will be acceptable in most situations, however, repeats at the 1 meter deviation level would be very desirable.

The radar modifications required to support repeat-pass deformation measurements include:

- Electronic steering of antenna beam with 1° accuracy over a range of ±20° (goal ±45°) in azimuth so that the repeat pass pointing requirements can be achieved for a wide variety of wind conditions aloft.
- Steering of antenna must be linked to the inertial navigation unit (INU) attitude measurements with an update rate capability of less than one second.

The desired flight track and radar electronic pointing capability desired for airborne repeat pass observations are illustrated in Fig. 1.

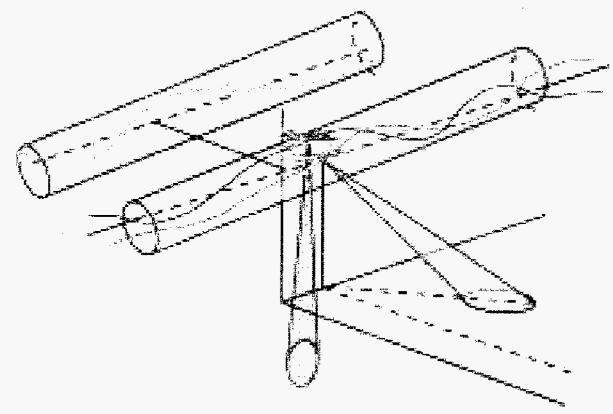

Fig. 1. To ensure high interferometric correlation for deformation measurements, the platform must repeat the trajectory within a specified tube (red and blue aircraft above). Electronic beam steering will compensate for the different aircraft yaw angles between passes. High resolution topographic mapping or tomographic imaging studies may also be supported by flying well defined baselines flying on a trajectory displaced by a spatial baseline from the reference trajectory as illustrated by the purple aircraft.

III. Radar Overview

The proposed radar for the UAV platform is a miniaturized polarimetric L-band radar for repeat-pass with optional later additions including a second across-track antenna for single-pass interferometry (elevation mapping capability), or a second antenna mounted along-track for along-track interferometry (velocity and current measurements) and additional frequencies of operation. The system will demonstrate key measurements including:

- Precision topography change for monitoring earthquakes both during and after a seismic event, for monitoring volcanic activity and for monitoring anthropogenic induced surface change such as subsidence induced by oil or water withdrawal, or other displacements of the surface from tunneling activities.
- Polarimetric interferometry, which can provide NASA with measurements of forest structure and sub-canopy topography.
- Polarimetric tomography, mapping in detail the vertical structure of a vegetated area.

A. Radar Parameters

Based on the science objectives and UAV platform characteristics, the key parameters of the radar design include are given in Table I.

TABLE I
RADAR PARAMETERS

Parameter	Value
Frequency	1.26 GHz (.2379 m)
Bandwidth	80 MHz
Pulse Duration	30 μs
Polarization	Quad Polarization
Range Swath	16 km
Look Angle Range	25°- 60°
Transmit Power	2.0 kW
Antenna Size	0.5 m 1.6 m
Altitude Range	2000-18000 m
Ground Speed Range	100 –250 m/s

In the following sections, we will outline the radar design for the L-band polarimetric RTI radar and its expected performance. We will also describe the hardware configuration and potential opportunities for technology demonstration.

B. Hardware Configuration

The radar instrument is made up of three major subsystems: the RF electronics subsystem (RFES), the digital electronics subsystem (DES) and the antenna subsystem. Fig. 2 is a simplified instrument block diagram of the L-band radar.

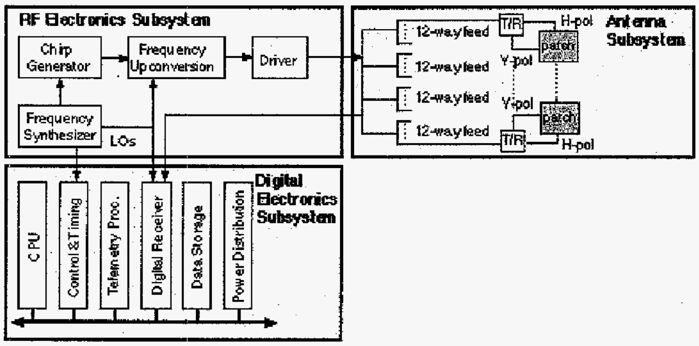

Fig. 2. Simplified instrument block diagram of the L-band Repeat-Pass Interferometer.

The RFES performs the transmit chirp generation, frequency up-conversion, filtering, and amplification during signal transmission. The RFES also controls the routing of the radar signal and the calibration signal.

The DES performs overall control and timing for the radar, frequency down-converts and digitizes the received echo, and routes the data to on-board data storage. The dual-channel digital receiver employs two high-speed analog-to-digital converters (ADCs) capable of handling down converted L-band signals. Filtering is performed by a combination of analog and digital filters implemented on field-programmable gate arrays (FPGAs). Radar data is recorded onto a 1.2 TB raid array along with associated metrology and radar telemetry information. The system includes the flexibility to operate both in interferometric and multi-frequency configurations even if the timing and bandwidth between the two frequencies are asynchoronous.

The antenna subsystem performs beam steering, transmission, and high power amplification on transmit and low noise amplification on receive. The antenna is a dual-polarization corporate-fed planar phased-array with 2 x 12 T/R modules and phase shifters for electronic beam steering from radar pulse-to-pulse. The peak transmit power for each T/R module is 100 W and the combined power of the 24 T/R modules is approximately 2.0 kW. Typical efficiency for L-band solid state amplifiers (SSPAs) is 40%. On the transmit end, there will be a polarization switch to direct the transmit signal to either the H or V-polarization feed of the antenna element. On the receive end, each T/R module will have two receiver front-ends (pre-select filter, high power limiter, and low-noise amplifier) to accommodate radar echoes from both the H and V-polarizations. The high degree of phase fidelity required for interferometric applications has lead to the inclusion of an active calibration scheme to track the phase variation of the array over temperature and time. Additionally, the antenna supports an elevation "monopulse" mode whereby the signals from the top and bottom half of the antenna can be recorded separately.

C. Estimate of Power, Weight, Volume

The estimated DC power for the L-band polarimetric RTI is just under 1.7 kW when the radar is transmitting. This is well within the capacity of the Gulstream III or the Proteus aircraft. The standby DC power should be on the order of 150 W. The active array antenna should weigh less than 40 kg since each T/R module weighs about 0.5 kg. The remainder of the radar electronics in the payload bay should weigh less than 150 kg (approximately 8 kg for the RFES, 25 kg for the DES, and 43 kg for cabling, power distribution, etc.).

Precise knowledge of motion and location is provided by the high precision INU and real-time differential GPS receivers [2]. Doppler centroid stability can be achieved by along track electronic beam-steering up to ±20° with a goal of ±45° linked to the INU attitude angle measurements. This dictates the radar design to utilize an active array antenna with transmit/receive (T/R) modules and phase shifters with a beam steering angle resolution of better than 1°.

Based on a data file provided by flight planning software, the UAVSAR will automatically initiate data takes at the appropriate locations throughout the flight. This approach was implemented on GeoSAR (a radar interferometric mapping system designed and built by JPL and currently operated by Earthdata International which is hosted on a Gulfstream II aircraft) with good results. Because of the autonomous requirement, this instrument must include BIT (Built In Test) capability and be able to determine failure at the unit level. A modular approach to delineation of logic functions in the instrument will assist in the addition of potential options in the future. Because the instrument is designed for modularity, reconfiguration for the addition of potential options or installation on a different platform should be feasible.

D. Radar Modes

The baseline mode for the single antenna UAVSAR implementation, is an L-band Polarimetry (PolSAR) mode. This mode combined with RTI will support not only deformation measurements (zero baseline case) but also high precision elevation mapping (non-zero spatial baseline) and polarimetric interferometry, e.g. for vegetation and volume scattering studies. The baseline system will also support Co-Polarized Monopulse (CoPM) measurements. This means that the signals recorded by the top and bottom halves of the antenna, can be recorded individually, which in essence provides for a very short baseline interferometric system. In this mode the system will not support a full quad-pol capability, only like (co-) polarized channels are recorded. Finally, the baseline system will support a Multi-Squint Differential IFSAR mode, allows the azimuth beam to cycles through multiple aspect angles (e.g. fore, broadside, and aft) on consecutive pulse transmissions as shown in Fig 3. This capability will allow experiments to measure vector displacements and for experiments to estimate vector displacements and atmosphere simultaneously.

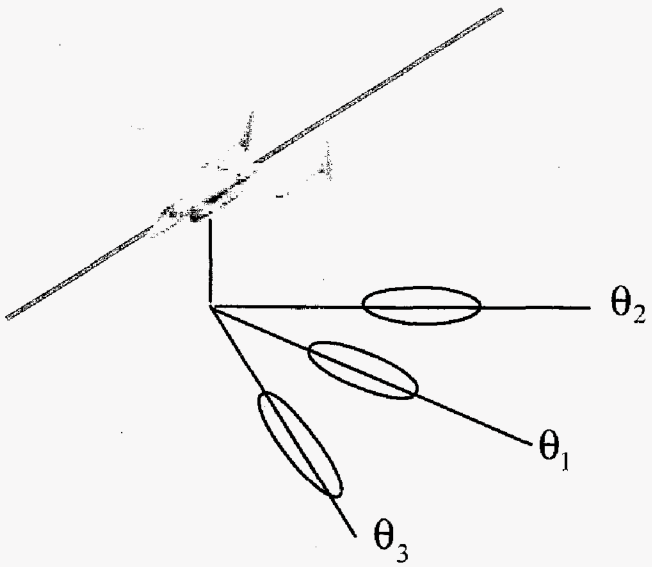

Fig. 3. Because the electronically scanned antenna has the capability to streer on a pulse-to-pulse basis three simultaneous SAR images can be generated at 3 distant squint angles as illustrated above. This will allow the generation of vector deformation maps as well as offer the potential of solving for tropospheric distortions to the deformation signal.

Furthermore, if the system is optionally augmented with a second antenna, the radar will support modes for single-pass across-track interferometric data acquisitions, including a Polarimetric Ping-pong Cross Track Interferometry mode (PolXTIP), and single antenna transmit, dual antenna receive modes Polarimetric Cross Track Interferometry (PolXTI1) and Polarimetric Cross Track Interferometry (PolXTI2). The previously mentioned monopulse modes will also be implemented to support modes for single or dual polarization acquisitions, Monopulse Cross Track Interferometry Horizontal Polarization (MXTIH), Monopulse Cross Track Interferometry Vertical Polarization (MXTIV), and Monopulse Cross Track Interferometry Dual Polariztions (MXTIP). Finally, if the second antenna optionally can be mounted along the fuselage relative to the primary antenna, the system will also support a Vector Along Track Interferometry for either Polarization (VATI) mode.

VII. Conclusion

The UAVSAR system under development will have completed the PDR by the time of this conference and is expected to have its first flight tests in the summer or fall of 2006 and complete its development in the summer of 2008. This system will be the first civilian SAR to incorporate an electronically scanned array and is expected to provide a robust repeat pass interferometric deformation mapping capability to the solid earth community. The system has been designed with portability and extensibility as primary factors and with future upgrades will be able to support a larger radar science community.

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